

# Non-degenerate Low Energy Leptogenesis

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(Dated: December 17, 2009)

## Abstract

We study a simple extension of the standard model to tackle the neutrino masses and matter-antimatter asymmetry in the universe. In our model, the baryon asymmetry is achieved by the leptogenesis mechanism without requiring any degeneracy of masses at the relatively low energy scale of 100 TeV.

arXiv:0907.1462v3 [hep-ph] 17 Dec 2009

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Although the standard model (SM) has enormous success in explaining all relevant existing experimental data, it leaves too many fundamental problems unanswered. For instance, what is the explanation for fermion masses, such as small neutrino masses? How to understand the matter and anti-matter asymmetry as well as dark matter and dark energy of the universe? It is generally anticipated that there is new physics in higher energy regions. However, most of theories require the energy scale as high as the scale of grand unified theories of  $10^{15}$  GeV, which are hard to be tested directly by experiments.

In this paper, we consider a new model with neutrino masses generated radiatively at one-loop level and the baryon asymmetry in the universe (BAU) achieved by the leptogenesis mechanism at the energy scale around 100 TeV. We introduce two new neutral leptons  $N_i$ , two new doublet scalars  $\zeta$  and  $\eta$  without vacuum expectation values (VEVs), and one singlet scalar  $S$  with the VEV of  $v_S$ . We impose two discrete symmetries,  $Z_2$  and  $Z'_2$ , for the new particles as shown in Table I. The relevant Majorana mass terms, Yukawa couplings and

TABLE I: New particle masses and transformations under the discrete symmetries of  $Z_2$  and  $Z'_2$ .

New Particle	$N_1$	$\eta$	$N_2$	$\zeta$	$S$
Mass	$M_1$	$M_\eta$	$M_2$	$M_\zeta$	$M_S$
$Z_2$	−	−	+	+	−
$Z'_2$	+	+	−	−	−

scalar interactions involving the new particles can be written as

$$\frac{M_i}{2} N_i^c N_i + y_{\alpha 1} \bar{L}_\alpha \eta N_1 + y_{\alpha 2} \bar{L}_\alpha \zeta N_2 + \lambda_S N_1^c N_2 S + \frac{\lambda}{2} (\phi^\dagger \eta)^2 + \frac{\lambda'}{2} (\phi^\dagger \zeta)^2 + \frac{\mu_S}{2} \eta^\dagger \zeta S + \text{H.c.}, \quad (1)$$

where  $i = 1, 2$  and  $\alpha = e, \mu, \tau$  are the flavor indexes,  $L_\alpha$  are the lepton doublets and  $\phi$  is the Higgs boson in the SM. In our study, we will assume the mass hierarchies of  $M_{\zeta_0} < M_\zeta < M_1 < M_\eta$  and  $v < M_1 < M_2$ , where  $v \simeq 174$  GeV is the SM Higgs VEV. The two discrete symmetries are broken to a diagonal one by the VEV of  $S$ . As a result, from Eq. (1) mixing terms between  $\eta$  and  $\zeta$  and  $N_1$  and  $N_2$  are induced, given by

$$\frac{\mu_S v_S}{2} \eta^\dagger \zeta + \lambda_S v_S N_1^c N_2 + \text{H.c.}, \quad (2)$$

respectively. We remark that the first term in Eq. (2) is similar to the soft breaking term proposed in Ref. [1].

The leptogenesis mechanism in our model is provided by the decays of  $N_1$  as shown in Fig. 1. In the figures, the crosses represent the mixings in Eq. (2). For the decay width

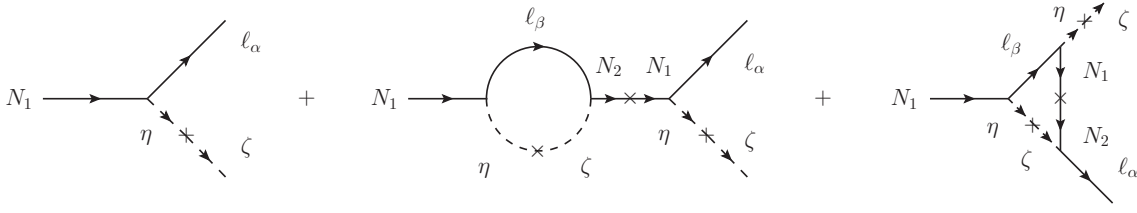


FIG. 1: Tree and one-loop diagrams for  $N_1 \rightarrow \ell_\alpha \zeta$ .

of  $N_1$ , in addition to the tree diagram in Fig. 1 (left), there is a channel, shown in Fig. 2. Hence, we obtain

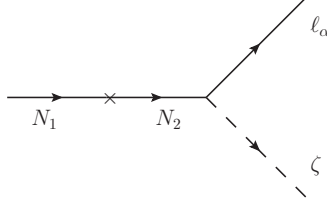


FIG. 2: Contribution to the decay  $N_1 \rightarrow \ell_\alpha \zeta$  from the fermion mixing.

$$\begin{aligned} \Gamma_{N_1} &= \sum_{\alpha} \Gamma(N_1 \rightarrow \ell_{\alpha}^{\mp} \zeta^{\pm}) = \frac{(M_1^2 - M_{\zeta}^2)^2}{16\pi M_1^3} \left[ (y^{\dagger} y)_{11} \left( \frac{\mu_S v_S}{M_{\eta}^2} \right)^2 + (y^{\dagger} y)_{22} \left( \frac{\lambda_S v_S}{M_2} \right)^2 \right] \\ &\simeq \frac{M_1 v_S^2}{16\pi} \left[ (y^{\dagger} y)_{11} \left( \frac{\mu_S}{M_{\eta}^2} \right)^2 + (y^{\dagger} y)_{22} \left( \frac{\lambda_S}{M_2} \right)^2 \right]. \end{aligned} \quad (3)$$

The  $CP$  asymmetry

$$\varepsilon \equiv \sum_{\alpha} \frac{\Gamma(N_1 \rightarrow \ell_{\alpha}^{-} \zeta^{+}) - \Gamma(N_1 \rightarrow \ell_{\alpha}^{+} \zeta^{-})}{\Gamma(N_1 \rightarrow \ell_{\alpha}^{-} \zeta^{+}) + \Gamma(N_1 \rightarrow \ell_{\alpha}^{+} \zeta^{-})} \quad (4)$$

is similar to that in the standard leptogenesis [2], and can be estimated as

$$\varepsilon \simeq \frac{v_S \sum_{\alpha} |y_{\alpha 1}|^2 \text{Im}[\lambda_S (y^{\dagger} y)_{12}]}{8\pi (y^{\dagger} y)_{11} M_2} \left[ g \left( \frac{M_2^2}{M_1^2} \right) + f \left( \frac{M_2^2}{M_1^2} \right) \right], \quad (5)$$

where the functions

$$g(x) = \frac{\sqrt{x}}{1-x} \quad (6)$$

and

$$f(x) = \sqrt{x} \left[ 1 - (1+x) \ln \left( \frac{1+x}{x} \right) \right] \quad (7)$$

correspond to the contributions from the self-energy and vertex corrections, respectively. For the non-hierarchical and non-degenerate  $N_i$  mass spectrum, *i.e.*  $M_1 \lesssim M_2$  and  $M_2 - M_1 \gg \Gamma_{N_i}$ , one can estimate

$$g(x) + f(x) = -O(1), \quad (8)$$

and the  $CP$  violating parameter in Eq. (5) is reduced to

$$\varepsilon \simeq -\frac{1}{8\pi} \frac{1}{(y^\dagger y)_{11}} \text{Im} \{ [(y^\dagger y)_{12}]^2 \} \frac{v_S}{M_2}. \quad (9)$$

From the net BAU [3, 4]

$$\frac{n_B}{s} \simeq -\frac{28}{79} \varepsilon \frac{n_{N_1}^{eq}}{s} \Big|_{T=M_1} \simeq -\frac{1}{15} \frac{\varepsilon}{g_*} = 9 \times 10^{-11}, \quad (10)$$

where  $g_* \simeq 100$  is the number of relativistic degrees of freedom, we obtain

$$\lambda_S y_0^2 \sim 10^{-6} \frac{M_2}{v_S}, \quad (11)$$

where we have assumed  $y_0 = O(y_{\alpha i})$  with the non-hierarchical  $y_{\alpha i}$  and maximal  $CP$  violation.

The out-of-equilibrium condition can be written as [5, 6]

$$\Gamma_{N_1} < H(T = M_1) = \sqrt{\frac{4\pi^3 g_*}{45}} \frac{M_1^2}{M_{\text{Planck}}}, \quad (12)$$

where  $H$  is the Hubble constant and  $M_{\text{Planck}} \simeq 10^{19} \text{ GeV}$  is the Planck mass. Eqs. (3), (11) and (12) lead to the constraint

$$\left( \lambda_S + \frac{\mu_S^2 M_2^2}{\lambda_S M_\eta^2} \right) \frac{v_S}{M_1 M_2} \lesssim 10^{-8} \text{ TeV}^{-1}, \quad (13)$$

which is consistent with the relation in Eq. (11) for  $M_1 \gtrsim 100 \text{ TeV}$ . We emphasize that the suppression for the decay width of  $N_1$  in Eq. (3), which is needed to satisfy Eq. (12), is due to the mixing terms in Eq. (2) in contrast to the degeneracy of masses in the leptogenesis models of Refs. [1, 4]. We remark that the decays of  $\zeta^\pm \rightarrow \zeta_0 \ell^\pm \nu(\gamma)$  would help to avoid the dangerous relics from the singly-charged component of  $\zeta$ .

The neutrino masses are generated by the one-loop diagrams in Fig. 3 and can be written as [7]

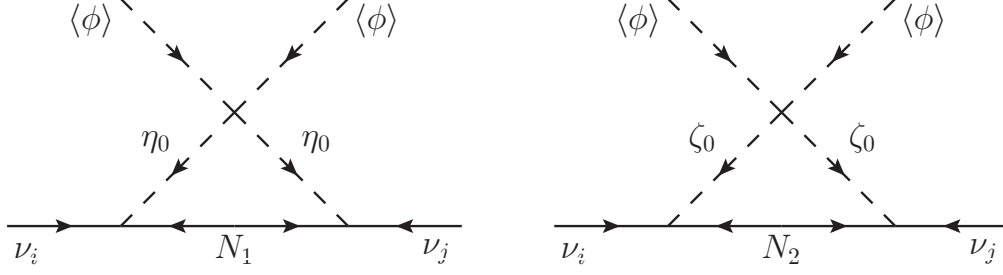


FIG. 3: Majorana neutrino masses generated at one-loop level.

$$(m_\nu)_{\alpha\beta} = \frac{\lambda v^2}{8\pi^2} \frac{y_{\alpha 1} y_{\beta 1} M_1}{M_\eta^2 - M_1^2} \left( 1 - \frac{M_1^2}{M_\eta^2 - M_1^2} \ln \frac{M_\eta^2}{M_1^2} \right) + \frac{\lambda' v^2}{8\pi^2} \frac{y_{\alpha 2} y_{\beta 2} M_2}{M_\zeta^2 - M_2^2} \left( 1 - \frac{M_2^2}{M_\zeta^2 - M_2^2} \ln \frac{M_\zeta^2}{M_2^2} \right), \quad (14)$$

where the relations  $M_\eta^2 \gg 2\lambda v^2$  and  $M_\zeta^2 \gg 2\lambda' v^2$  are used. Similar to the minimal seesaw model with two right-handed neutrinos [8], our model contains one massless neutrino with only the normal or inverted hierarchy of the neutrino masses. However, the extended model with three  $N_i$  could still allow the possibility of the quasi-degenerate neutrino masses. We should note that the considered model is more flexible in explaining the neutrino masses and mixings, in comparing with the original Ma's model [7], due to the new parameters in the neutrino mass formula (14).

We remark that our model may generate the leptogenesis at 100 TeV scale and explain the observable neutrino masses for the typical scales of  $\lambda/\lambda_S = O(10^{-2})$  and  $\lambda'/\lambda_S = O(10^{-2})$ , since the ‘‘Davidson-Ibarra’’ bound [9] is relaxed similar to Ref. [10]. The corresponding mass differences between the lightest and next-to-lightest (NL) neutral components of  $\zeta$  and  $\eta$  can be estimated as

$$M_{I_0^{\text{NL}}} - M_{I_0} \simeq \frac{|\lambda_I| v^2}{M_{I_0}} \sim 10 \text{ MeV} \left( \frac{m_\nu}{0.1 \text{ eV}} \right) \frac{\lambda_S v_S}{M_2} \quad (15)$$

with  $I = \zeta, \eta$  and  $\lambda_I = \lambda', \lambda$ . The lightest neutral component of  $\zeta$  is stable. However, it can not provide the dark matter density due to the small mass difference in Eq. (15), compare with the Inert Higgs Doublet model [11, 12, 13].

In summary, we have investigated a simple extension of the SM to generate the small neutrino masses at one-loop level and the observed BAU by the new low energy leptogenesis mechanism.

## Acknowledgements

We would like to thank Prof. Anatoly V. Borisov, Prof. Chuan-Hung Chen, Prof. Ernest Ma and Dr. Takeshi Araki for useful discussions. This work is supported in part by the Boost Program of NTHU and the National Science Council of R.O.C. under Grant No: NSC-95-2112-M-007-059-MY3.

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